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Effect of Freeze-Thaw and Wet-Dry Cycles on the Mechanical and Hydraulic Characteristics of Geothermal Mortars

D Zamora-Barraza[1], J Vilches[1], F Sierra[2] y H Bravo[2]

[1]Civil Engineering Department, Universidad Católica del Maule, Talca, Chile
[2]Undergraduate student of Construction Engineering, Universidad Católica del Maule, Talca, Chile

E-mail: dzamora@ucm.cl, jvilches@ucm.cl

Abstract. The appropriate performance of a vertical geothermal exchanger depends not only on the thermal properties of the elements that composed it, but also on the close contact between them to ensure the heat transfer. This contact can be affected by temperature, moisture and seismic tremor variations within the ground, generating cracks and leaks in the grout and thus compromising the integrity of the system. Grouts usually have a high water/cement ratio to provide an appropriate fluidity during the borehole filling, and bentonite is used to keep the cement of the mixture on suspension. The main purpose of this research is to determine according to the bentonite amount, the effects generated by the seasonal freeze-thaw and wet-dry cycles on the mechanical properties of a geothermal borehole grout. Adherence tests from the grout to the exchanger, as well as compressive and flexural strength tests to a mortar with bentonite in percentages of the cement weight (0%, 1%, 2%, 3%, 4% and 5%) has been carried out during the curing period and under the effects of 7 freeze-thaw and wet-dry cycles, which simulates the annual freezing during the heating period and the movements of ground waters, respectively. According to the results, it is concluded that mechanical properties of the mortar decrease as the bentonite amount increases and the pipe-mortar adherence is the most affected by the freeze-thaw and wet-dry cycles.

1. Introduction

The grout of the vertical geothermal boreholes has a major role in the heating transfer system; it provides mechanical stability and guarantees the heat transfer between the geothermal probes and the ground. The desirable properties for an adequate grout are: high thermal conductivity, volumetric stability under temperature and pressure changes, low hydraulic permeability to avoid ground water infiltration and contamination, and to keep a close contact with the probe. During borehole injection, the grout must be fluid enough to be injected and it has to have a higher density than the drilling muds so it can be extracted without mixing with them.

There are mainly two types of geothermal grouts, bentonite-based (thixotropic mud) and cement-based grouts (material with latent hydraulicity) [1]. The first ones have the property of being fluid when are injected and act as plastic solids during rest. The bentonite-water suspension was the first type of grout used for geothermal boreholes due to its vast use on drillings; however, its low thermal conductivity and volumetric instability have promoted the use of complementary additions [1]. Some additions such as silica sand, considerably improve the thermal conductivity of bentonite mixtures, increasing the heat power dissipated by unit length at 25% [2]. Lee et al. [3] studied the influence of both silica sand and graphite addition on thermal conductivity, mixture viscosity and volumetric stability of bentonite grouts. Both viscosity and thermal conductivity increased because of silica sand and graphite addition, however, the graphite had a higher impact reaching 3 W/mK versus 1.4 W/mK of silica sand. Furthermore, it was concluded that the volumetric stability of bentonite at moisture changes depended on the amount of montmorillonite, a special type of clay that provides higher expansiveness and lower retraction, guaranteeing in this way, an ideal borehole sealing.

Another aspect to have in mind is hydraulic permeability. It is known that if the bentonite grout is exposed to high concentrations of water-dissolved divalent cations the hydraulic permeability can be reduced due to monovalent cations exchange within the mixture [4]. Divalent cations are usually located in ground waters and they can increase the permeability and reduce the expansiveness of the fill, especially if it is exposed to wet-dry [4] and freeze-thaw cycles [5], this reduced expansiveness impairs the intimate mortar-pipe contact, decreasing the performance of the geothermal system, as will be seen later in this research. The wet-dry cycles are related to the level changes of ground waters around the boreholes, which can affect or not affect its performance. The freeze-thaw cycles are produced by the temperature changes generated by the geothermal system in order to cool or heat; a high heat power can freeze the exchanger pipe if it does not have enough length or a high thermal resistance.

Parallel studies of cement and water-based grouts have been carried out. Allan et al. [6] studied the adherence, permeability, thermal conductivity and mechanical resistance properties of grout, which improved under low water-cement ratios. With an optimal ratio of 0.4, thermal conductivities similar to bentonite mortars (0.75-0.78 W/mK) were obtained and with the addition of silica sand it reached between 2.16-2.53 W/mK during the dry-saturated state. Due to the addition of silica fume and amino vinil silane, Xu and Chung [7] increased the thermal capacity of cement mortars in 50% and its thermal conductivity in 38%, as well as the compressive strength. Tan et al. [8], on the other hand, studied the compressive strength of bentonite, fly ashes and silica fume reinforced grouts. Both fly ashes and silica fume have a major role in compressive strength, showing maximum strengths of 17.1 MPa with bentonite, fly ashes and silica fume proportions of 0%, 10% and 20% respectively. Even though the bentonite barely affects the compressive strength, it can be used to improve rheological characteristics, grout stability and to effectively seal boreholes, due to its expansive properties. Borigna et al. [9] studied the effects of freeze-thaw cycles over mechanical and thermal properties of limestone, silica sand and neat cement mortars. Except for the neat cement mortars and probably because of the non-saturation of its core, the results showed no significant damage related to the cycles. While neat cement mortar presented no flexural strength, its core kept thermal conductivity, denoting that any loss of the geothermal system efficiency is linked to the increment of the mortar-pipe thermal resistance, as a result of the grout fractures.

The following research is based on previous works, in order to complement the studies related to cement and bentonite mortars, which stabilizes the mixture and reduces the water/cement ratio without compromising its fluidity and give a more rational usage to cement. Furthermore, the effects generated by the freeze-thaw and wet-dry cycles on the mechanical properties of compressive and flexural strength as well as the adherence between the mortar and the pipe exchanger are studied.

2. Materials and Methods

The evaluated grouts were made of cement, water and bentonite in different proportions; the bentonite keeps the cement on suspension and avoids the sedimentation when it is used in high water/cement ratio (w/c), which facilitates the fluidity of the grout mixture, moreover, it properly sealed the boreholes thanks to its expansive properties. In this research, two levels of w/c ratio (0.33 y 0.6) and 6 bentonite levels by cement weight (0%, 1%, 2%, 3%, 4% and 5%) were used, and the following 4 curing conditions of the mortar were simulated: Dry Curing (D), a low quality curing in a dry ground drilling; Regular Saturated Water Curing (S) for wet or saturated soils; Wet-Dry Cycles (WD), immersing test probes under water for 48 hours and then air drying them for another 48 hours, to simulate moisture changes of the soil due to ground water movements; and finally, Freeze-Thaw Cycles (FT), freezing/thawing the test probes at -5°C/10°C for 48 hours, to simulate the annual freeze/thaw cycles that geothermal boreholes can suffered during the winter and summer seasons. Each treatment lasted 28 days (7 cycles for WD and FT). Each mortar was named according to its treatment in the form $M_{WC, B, C}$ where the letter M refers to a mortar, WC is the w/c ratio (A=0.33 and B=0.60) and B the amount of bentonite (0% to 5%). The last letters C refer to the curing type or the applied cycle. For example, $M_{A,0,FT}$ correspond to a mortar with a w/c ratio = 0.33, a bentonite content of 0% and FT is the freeze-thaw cycle.

After each treatment, compressive and flexural strength test were carried out according to the applied regulation ([10] and [11], respectively). Likewise, the adherence between the mortar and the pipe exchanger was evaluated through a compressive test, according to the proposed methodology by Pascual et al. [12]. Here a polypropylene pipe is inserted in a mortar probe and attached to a simple compressive test, where the load is in contact with the projecting part of the pipe, generating the effort on the pipe-mortar contact area. Thanks to the mechanical characterization of mortars, it is possible to determine the effect that the different conditions are exposed to, has on the borehole grouts. Thus, compressive strength allows to estimate the confinement and flexural strengths, the damage produced by landslides and the adherence, the probability of a decoupling between the exchanger pipe and the grout, which produce gaps resistance to the heat transfer, reducing the system performance.

3. Results and analysis

3.1. Adherence

The results of adherence from each mortar are shown in table 1.

Table 1. Adherence results (MPa).

w/c ratio	0.33		0.60					
Bentonite %	0%	2%	0%	1%	2%	3%	4%	5%
Freeze-thaw cycle	0.291	0.300	0.694	0.652	0.606	0.571	0.570	0.534
Wet-dry cycle	0.623	0.449	0.478		0.539			
Saturated curing	0.458	0.374	0.738	0.660	0.633	0.616	0.583	0.551
Dry curing	0.568	0.395						

Figure 1 shows the adherence results of WD mortars in function of the bentonite amount for a w/c ratio= 0.33, whereas figure 2 shows the adherence results of FT mortars with a w/c ratio=0.60. Both graphics show that the bentonite tends to reduce the adherence between the mortar and the pipe exchanger in all curing types, being more noticeable in figure 2, where a wider bentonite range is showed. This reduction can be explained by the air gap generated in the mortar during the mix procedure (figure 3), which lately restrict the connection between the mortar and the pipe; besides, the bentonite does not participate in the pipe connection, decreasing the cement contact with surface.

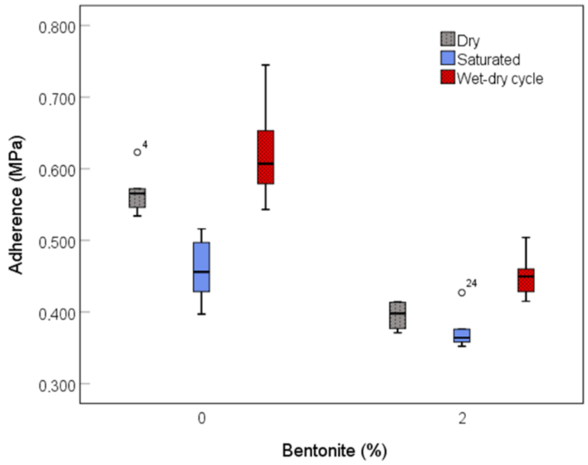

Figure 1. Adherence between the mortar and the exchanger pipe for D, S curing and WD cycle (w/c= 0.33).

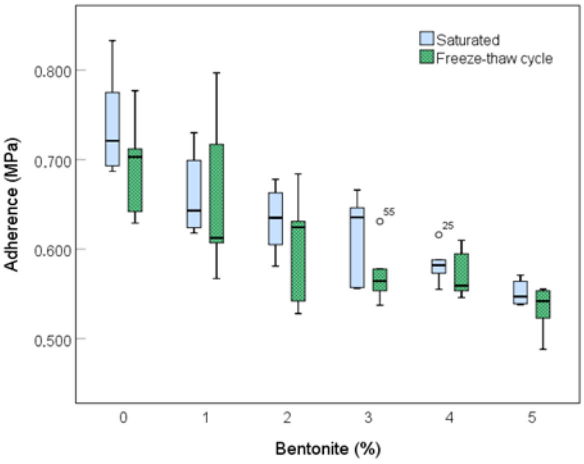

Figure 2. Adherence between the mortar and the exchanger pipe for S curing and FT cycle (w/c= 0.60).

Figure 3. Difference between mortars with and without bentonite. The bentonite content increases the air trapped in the mixture. Left: $M_{B,0}$, Right: $M_{B,5}$.

In the case of wet-dry cycle (figure 1), the highest adherences were obtained with the WD cycle, followed by D and last S, both in bentonite at 0% and 2%. For each curing type, the results are noticeably inferior with bentonite at 2% showing the mean differences of 30%, 18% and 28% for D, S and WD curing, respectively. Since most of the time mortars are injected on thermally conductive soils with a relatively high moisture, the cyclical variation of moisture or the borehole drying are no threats for the adherence from the mortar to the exchanger, the w/c ratio and the bentonite range used in the mixtures.

In the case of freeze-thaw cycle (figure 2), the results are slightly higher for S curing, although there are no significant differences (mean variation lower than 4.1%), so the cyclical freezing phenomenon of the mortar should not affect the pipe adherence, at least during the 7 evaluated cycles and in a w/c ratio= 0.6.

Figure 4 shows the adherence results for both cycles and the S normal curing of the mortar, comparing the combined effects of bentonite (0% and 2%) and w/c ratio (0.33 y 0.60).

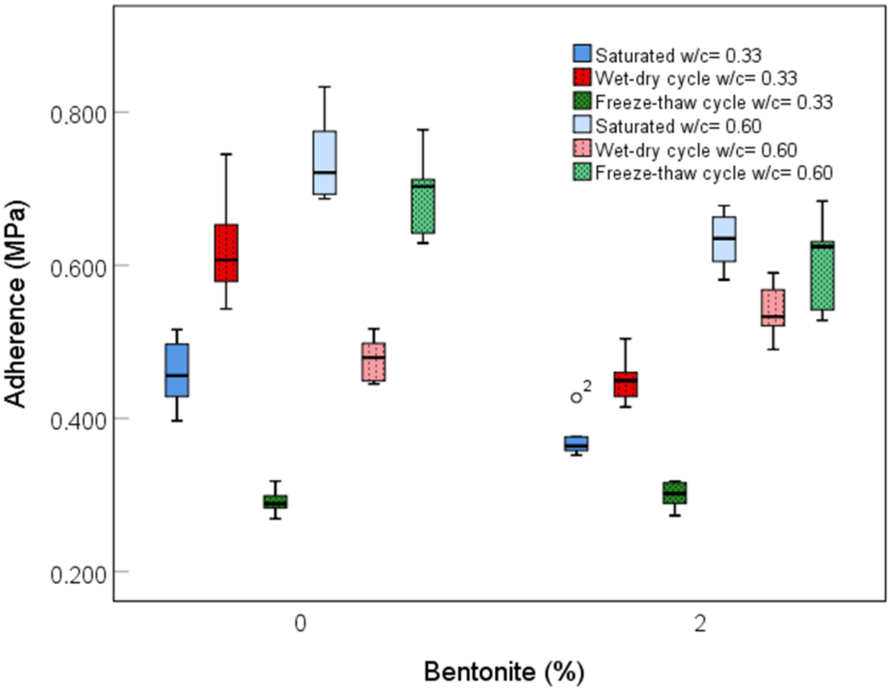

Figure 4. Comparison between WD and FT cycles, according to the bentonite content and w/c ratio.

For a w/c ratio= 0.33, the WD cycle obtained better adherence results than the saturated curing, whereas the FT cycle obtained the lowest adherence, at 0% and 2% of bentonite. However, the situation changes for w/c=0.60; the WD cycle obtained the lowest adherence of all, whereas the FT cycle remains slightly under the saturated curing. This indicates that the water cement ratio has an impact on the saturation cycle that effect the mortar-pipe adherence more than the bentonite amount in the evaluated range (0%-2%).

Therefore, the WD cycle shows a higher dependence on the w/c ratio than the FT cycle, becoming the most relevant phenomenon to consider in the mortar designs. For a low w/c ratio (0.33) mortar without bentonite, the most considerable damages come from the FT cycles that can reduce the adherence by a mean of 36%. Whereas for a mortar with high w/c ratio (0.60), the bentonite is necessary to keep the suspension of the cement mixture and the most considerable damages come from the WD cycles that can reduce the mean adherence of 15%. However, this loss is not comparable with the adherence difference produced by w/c ratio reduction. To go from a $M_{B,2}$ to a $M_{A,2}$ mortar produced a reduction of 41%. The same happened in a mortar without bentonite; a w/c ratio changed from 0.60 to 0.33 produced an adherence loss of 38%. In summary, the biggest adherence loss, in descending order, are due to w/c ratio reduction, FT cycle to a low w/c ratio, WD cycle to a high w/c ratio and to a bentonite increase.

3.2. Compressive and flexural strength

The bentonite effect in the compressive and flexural strength of S and FT mortars is shown in figure 5 and figure 6.

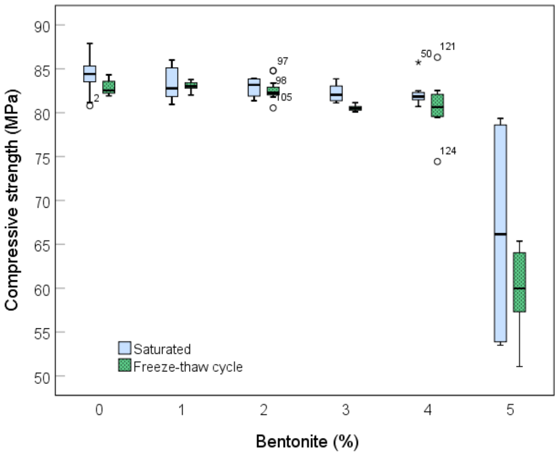

Figure 5. Compressive strength results for S and FT mortars.

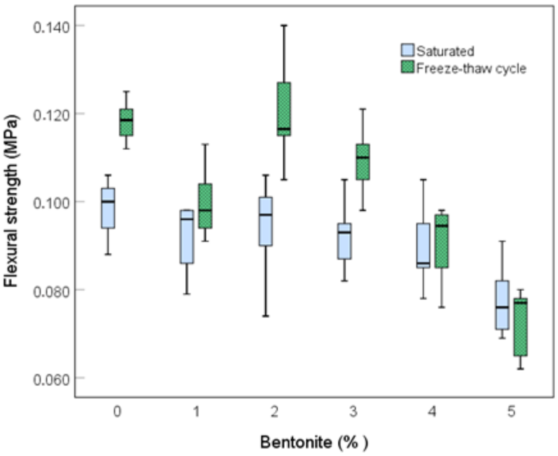

Figure 6. Flexural strength results for S and FT mortars.

Both compressive and flexural strengths are negatively affected by low bentonite amounts. Compressive strength shows no relevant variations under 4% (figure 5), according to the measure distributions, but $M_{B,5,S}$ and $M_{B,5,FT}$ mortars have a considerably lower result and a wider distribution which causes must be associated with the amount of bentonite. The freeze thaw cycle shows no relevant variations of compressive strength in comparison to a regular saturated curing process; however, it shows a slightly lower reaction, with maximum variations of 2%. On the other hand, the flexural strength shows a decreasing tendency at 3% (figure 6). The differences produced by the FT cycle in relation to the S mortars are perceptible, between 0% and 3% of bentonite, producing variations from 8.1% to 27.4%, with higher results in FT mortars; however, these differences tend to disappear at higher percentages. Both mechanical properties tend to decrease because bentonite does not participate in the hardening of cement, weakening the concrete structure.

The comparison of compressive and flexural strength between the cycles is represented in figure 7 and figure 8, respectively. Here, bentonite concentrations of 0% and 2% as well as w/c ratio= 0.6 were used. In both cases, there are no significant variations because of sample dispersion, in some cases too steep, such as the $M_{B,0,S}$ mortars under compression and the $M_{B,2,WD}$ mortars under bending. In general terms, the compressive strength was slightly superior in saturated mortars, followed by FT mortars and finally WD mortars, with a maximum mean resistance loss of 2.52%.

The flexural strength results show a clear difference between S and FT mortars, where the freeze-thaw cycles do not adversely affect the flexural strength, on the contrary it makes them more resistant (20% and 27% for 0% and 2% of bentonite). Meanwhile, the WD mortars present intermediate bending values for 0% of bentonite and a high dispersion at 2% to demonstrate some tendencies.

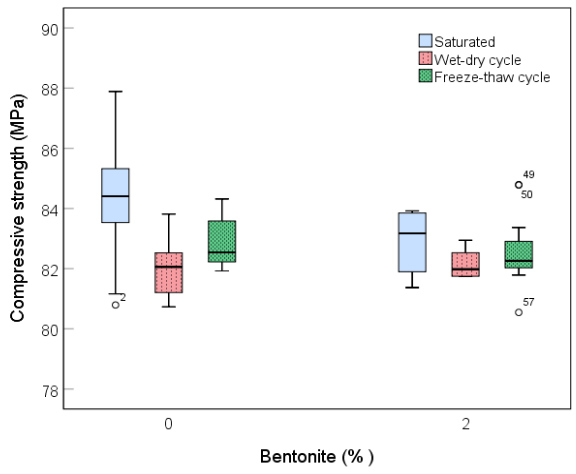

Figure 7. Comparison of compressive strengths of WD and FT cycles.

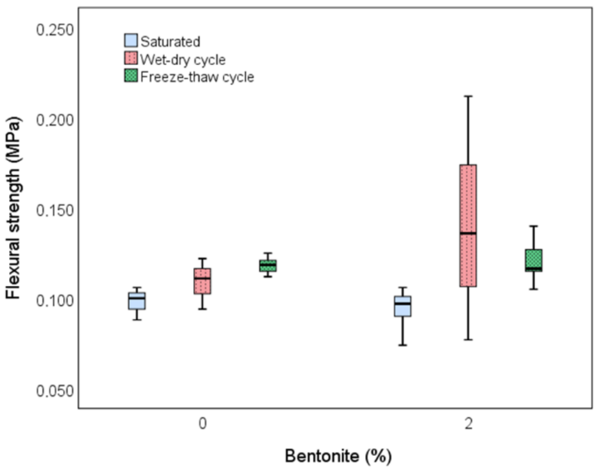

Figure 8. Comparison of flexural strengths of WD and FT cycles.

4. Conclusions

One of the main conclusions is that the clear bentonite tendency is to reduce the mechanical properties of concrete; however, it is essential to formulate grouts that required a high water/cement ratio and fluidity; for this reason, it is essential to properly combine each component to minimize the negative effects.

The freeze-thaw and wet-drying cycles affect the mechanical properties in different ways. The adherence is affected mainly by water/cement ratio, thus it is recommended in high values. For a $M_{A,0}$ mortar, the biggest damages are produced during the freeze-thaw cycles (-36%), whereas for a $M_{B,2}$ mortar, the biggest damage is produced during the wet-dry cycles (-15%). The compressive and flexural strengths obtained better results with lower bentonite proportions, and they perform well in freeze-thaw cycles with 0% to 3% of bentonite, whereas the wet-dry cycle does not noticeable affect the compressive strength and tends to improve flexural strength.

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